The Success Story of SMOG-P, the World's Smallest Satellite

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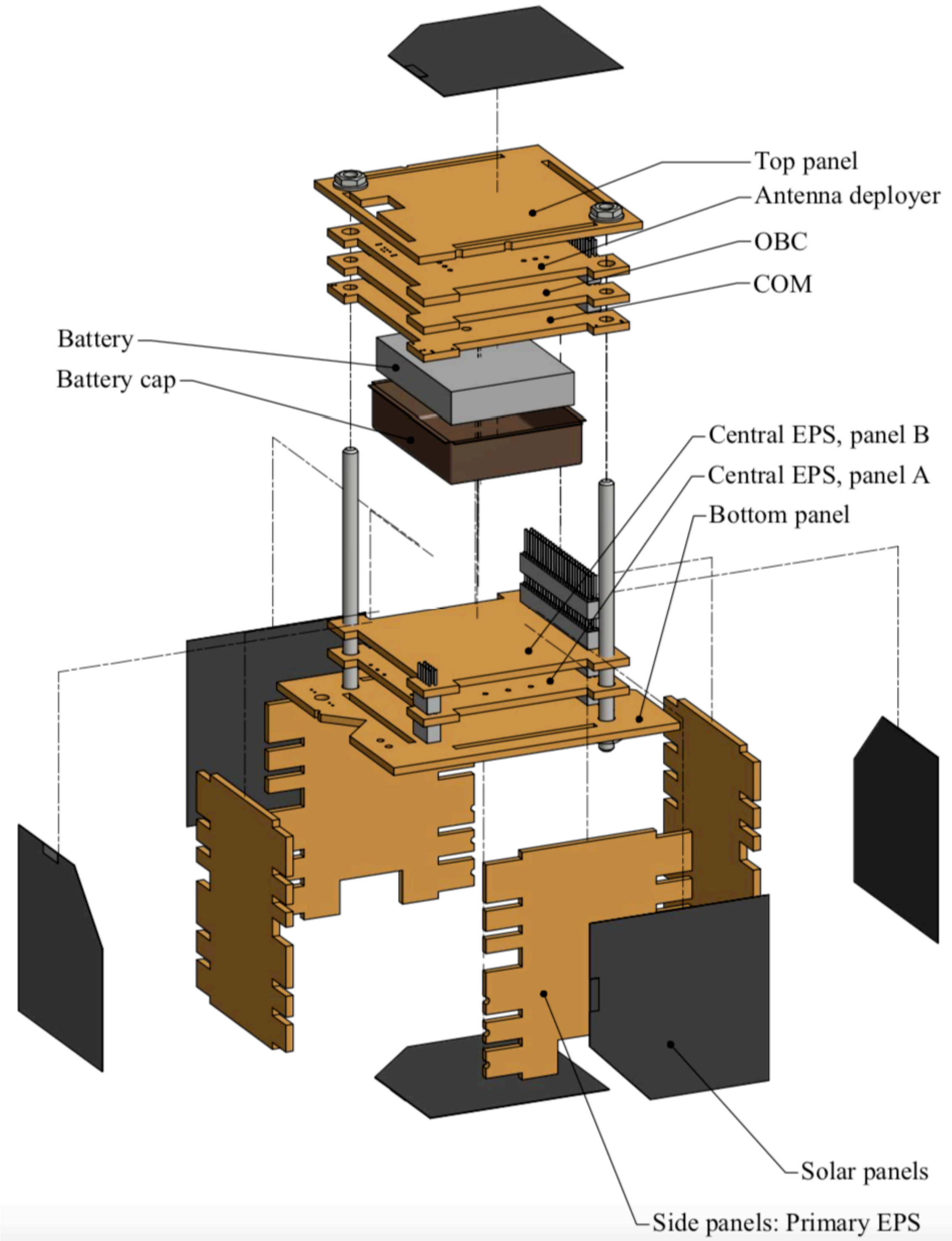
Back in 2014 a group of young engineering students and their lecturers at Budapest University of Technology and Economics, started to develop the smallest scientific satellite of the world in the size of 5×5×5 centimeters (2×2×2") and total weight of 250g (8.82oz). The name SMOG is symbolizes its primary mission to map electromagnetic pollution around Earth, which is a first in class measurement never published before.

Beneath the small on-board spectrum analyzer used for the electro smog measurement as primary payload, an experimental dosimeter payload (subject of an upcoming article) and other technology demos were launched to space. Apart from the primary payloads, the satellite contains 20 temperature sensors to measure the thermal behavior of the construction, 2 magnetometers, 2 gyroscopes, and 6 light sensors. Numerous voltages and currents are also monitored to provide housekeeping data.

Hardware design seemed to be the most challenging for young engineering students. In this small volume the solar cells are able to generate only around 0.3 W electrical power, that could be stored in the battery and used for communication, data processing and to power the payloads. We had to design the electronics with the highest possible efficiency and optimize the power consumption of every system to keep a positive energy balance. The battery is charged during the sunny side of the orbit and the stored energy is used to supply the systems when there is no sunlight in the shadow of our planet. Our team decided to build the structure of this small sat with redundant systems for the highest reliability to succeed with our mission. This means that we had to design at least two of our systems in a tiny volume. Only printed circuit boards that carry the electronics were used to create the buildup, 2256 electrical parts were used with a few mechanical components. The following figure illustrates the buildup.

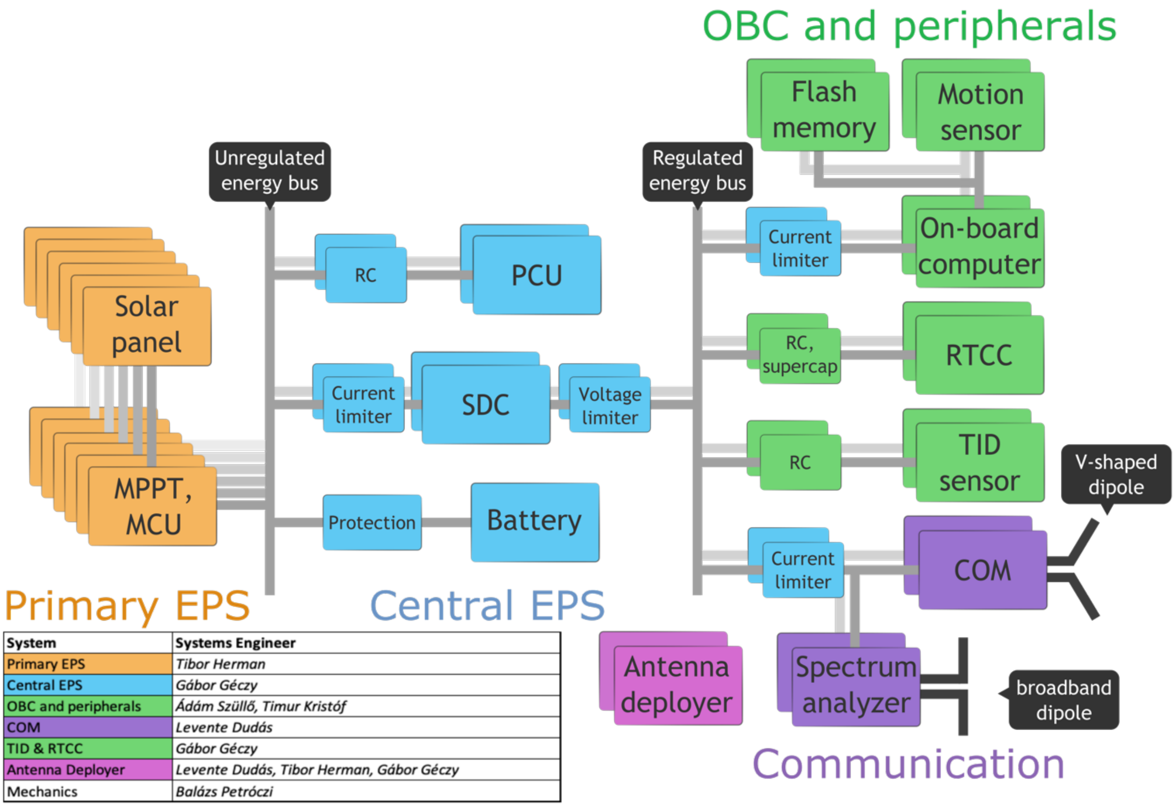


1. Figure: The buildup of the SMOG satellite architecture

The solar cells generate electrical energy from the sunlight that powers SMOG's systems. Maximal Power Point Tracker (MPPT) circuits placed to the inner side of the outer boards of the Primary Electrical Power System to convert the energy of the solar cells to the energy bus to supply the Central Electrical Power System.

The Central EPS collects the energy from the 6 sides and using it to charge the Lithium-Ion battery or supply the payloads through a high efficiency power supply and protection circuits. (This was the author's task to design as his master's thesis).

The Power Control Unit (PCU) controls the EPS, collects data from the power usage and forwards it to the On-Board Computer (OBC).
The OBC has the task of data processing and to control all other systems.
The communication system (COM) maintains reliable radio communication with Earth to download the results and receive uplink commands. The COM also includes the spectrum analyzer payload.
The Total Ionizing Dosimeter (TID) is a new experimental instrument with the mission to measure and monitor the radiation dose absorbed by the electronics during orbit.
An additional subsystem was used to place the antenna opening circuits and internal connections between some systems.

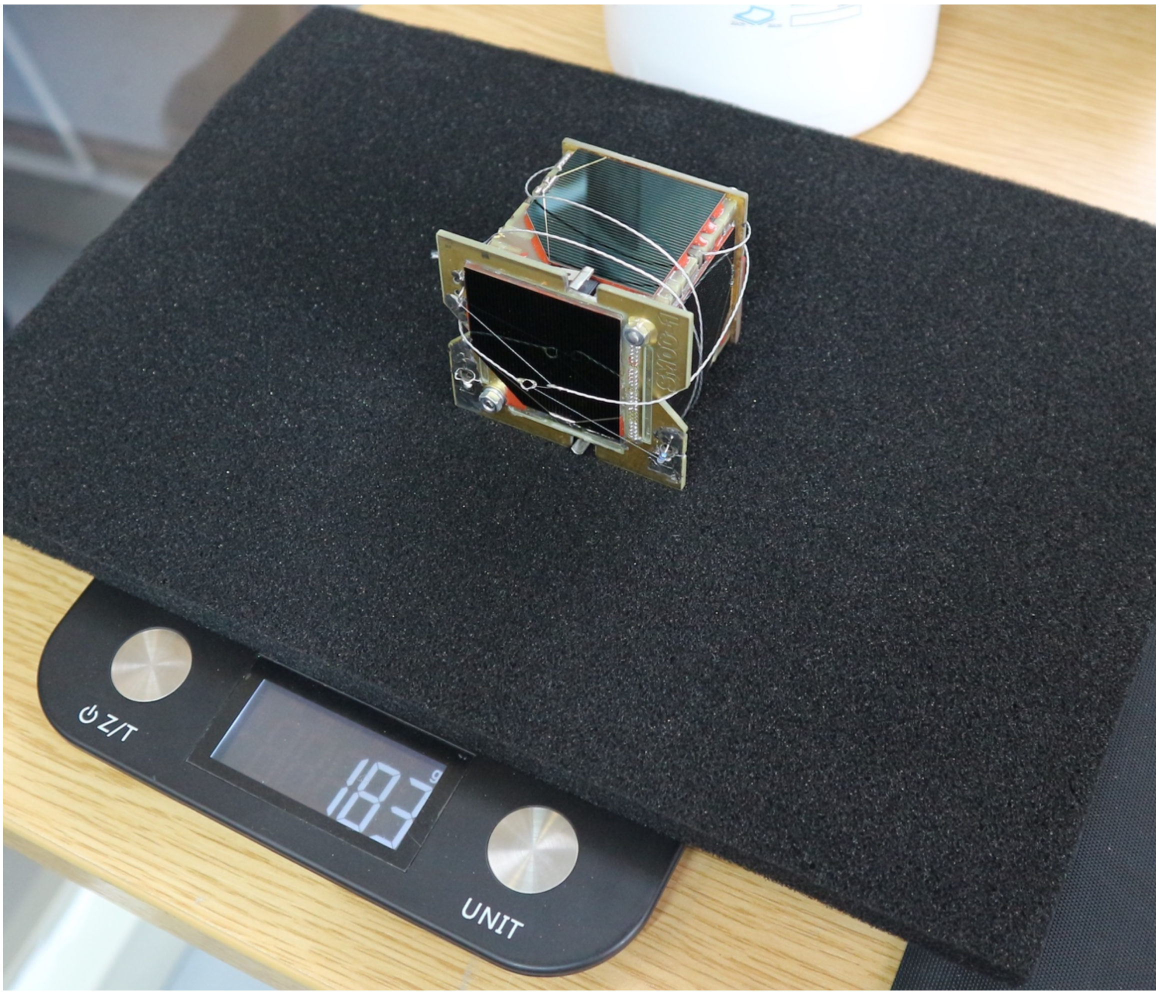


System	Systems Engineer
Primary EPS	*Tibor Herman*
Central EPS	*Gábor Géczy*
OBC and peripherals	*Ádám Szüllő, Timur Kristóf*
COM	*Levente Dudás*
TID & RTCC	*Gábor Géczy*
Antenna Deployer	*Levente Dudás, Tibor Herman, Gábor Géczy*
Mechanics	*Balázs Petróczi*

2. Figure: SMOG system block diagram

Our team was working on building SMOG for years, and we prepared the structure to survive the harsh environment of space. Extreme temperatures were expected but we could perform only simulations to estimate the thermal behavior, since there were no available measured data from such a small satellite structure before. The subsystems were tested in climatic chambers between -45 and +85 °C (-49 to +185 °F). Tests were performed in thermal-vacuum chamber, and we examined the hardware with vibration tests on shaker systems to ensure that the tiny structure of SMOG will survive the huge mechanical stress during the launch of the rocket. Special validation tests were performed to ensure the proper results from the primary payloads. The spectrum analyzer was validated by high altitude balloon tests, and irradiation tests were performed to validate the dosimeter instrument.
We nearly finished SMOG in 2017, but it was hard to find a way to start the mission in space. There were no prepared launch services and ejecting structures for this new tiny structure

called "PocketQube", unlike those that already existed and were commonly used to deploy CubeSats for years. Finally, we found an opportunity. In September 2019, we carried the Proto Flight Model named SMOG-P to Scotland, where we integrated it to the deployer of Alba Orbital. This was the last time we saw our tiny satellite which weighted only 183 grams (6.46 oz) during the integration.



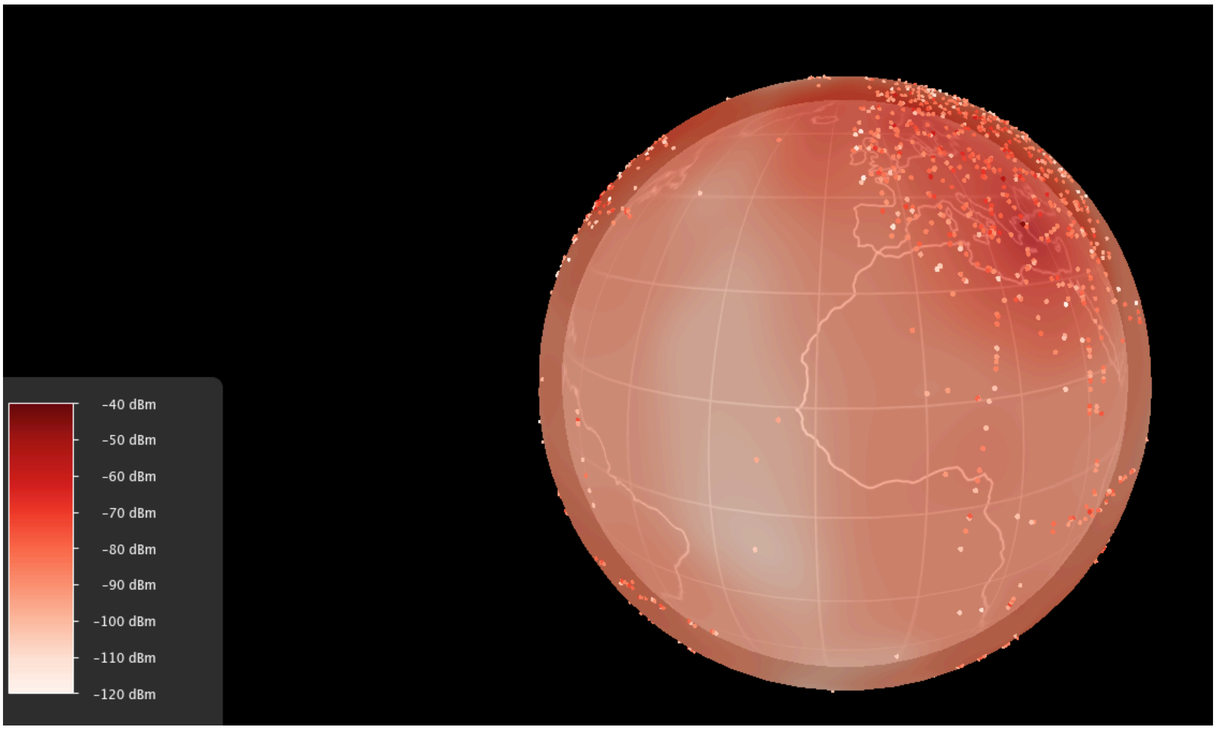
3. Figure: The final weight of SMOG-P during the integration

After this procedure the deployer was carried to the launch complex of RocketLab in New Zealand, and was attached to the payload plate of an Electron rocket. SMOG-P needed to travel to nearly the farthest point of Earth from its place of birth Hungary, to finally get out to space in 6th of December 2019 via the 10th mission of RocketLab's Electron rocket called "Running Out of Fingers". This eye-catching picture of the start event was taken by Brendan Gully Photography.

4. Figure: The 10th Launch of RocketLab's Electron rocket, Mahia Peninsula, New Zealand - 6 December, 2019

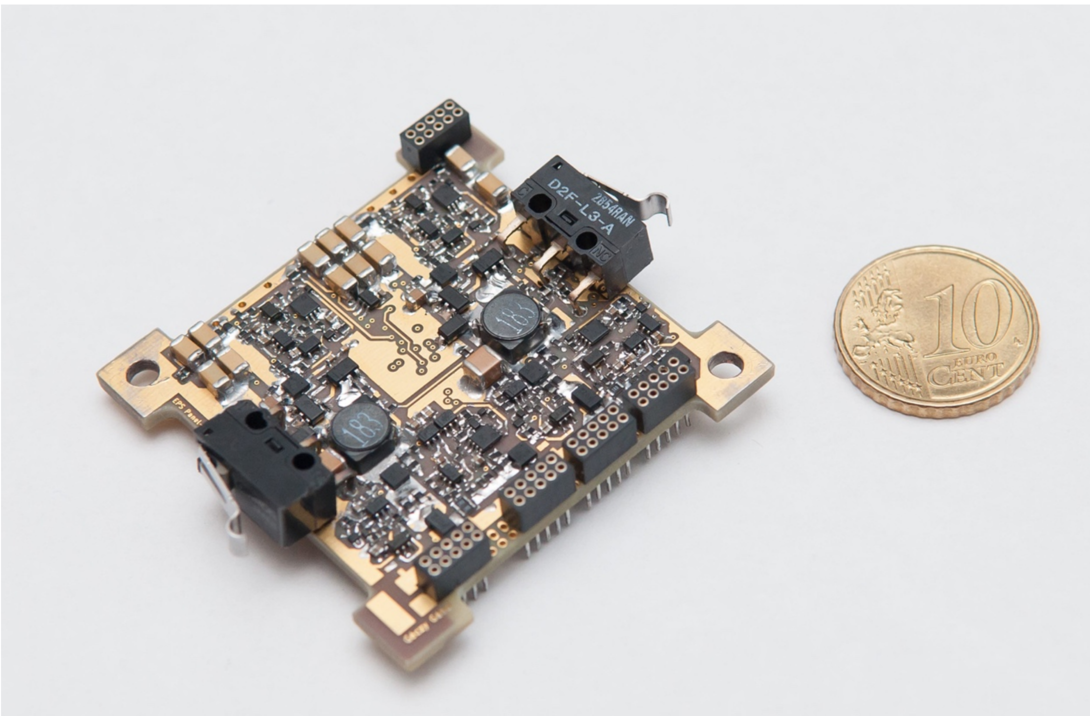
The launch and deployment were one of the hardest parts of the mission. Critical processes like starting the system and antenna opening causes failure for a lot of satellite missions.
A few hours after the launch the first approximations about the orbit were published, and radio amateurs around the world confirmed that SMOG-P has begun its mission and sending radio signals from space. SMOG-P set a new world record as there was no such small working satellite before.

The team designed a standalone software for the public, so everyone can decode the signals of SMOG and forward it to our server for further processing. Since the beginning of the mission more than 206000 data packets were collected (as of 06.08.2020) around the world that contains useful data from SMOG-P. Some of these data were used to create the first map about electromagnetic pollution caused by human activity.



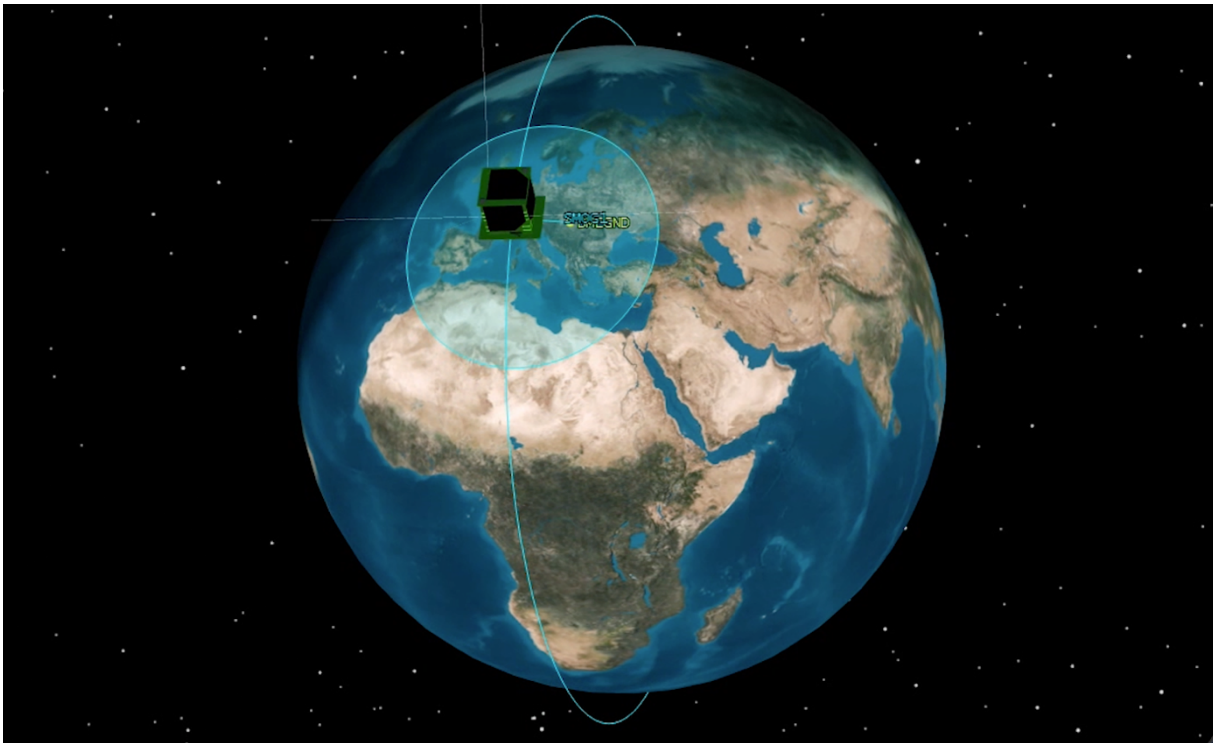
5. Figure: 3D map about electromagnetic pollution levels measured by SMOG-P around Earth

The measurement data showed some interesting anomalies. From the beginning of the mission we often experienced that the protection circuits of the Central EPS had to power down the active systems and switch to the backup systems. The most likely possible reason for that is when a high energy particle hits the electrical parts which causes single event latch-ups. Fortunately, the designed protection circuits handle these events perfectly, they saved the mission many times.



6. Figure: The power supply and protection circuits of the Central EPS

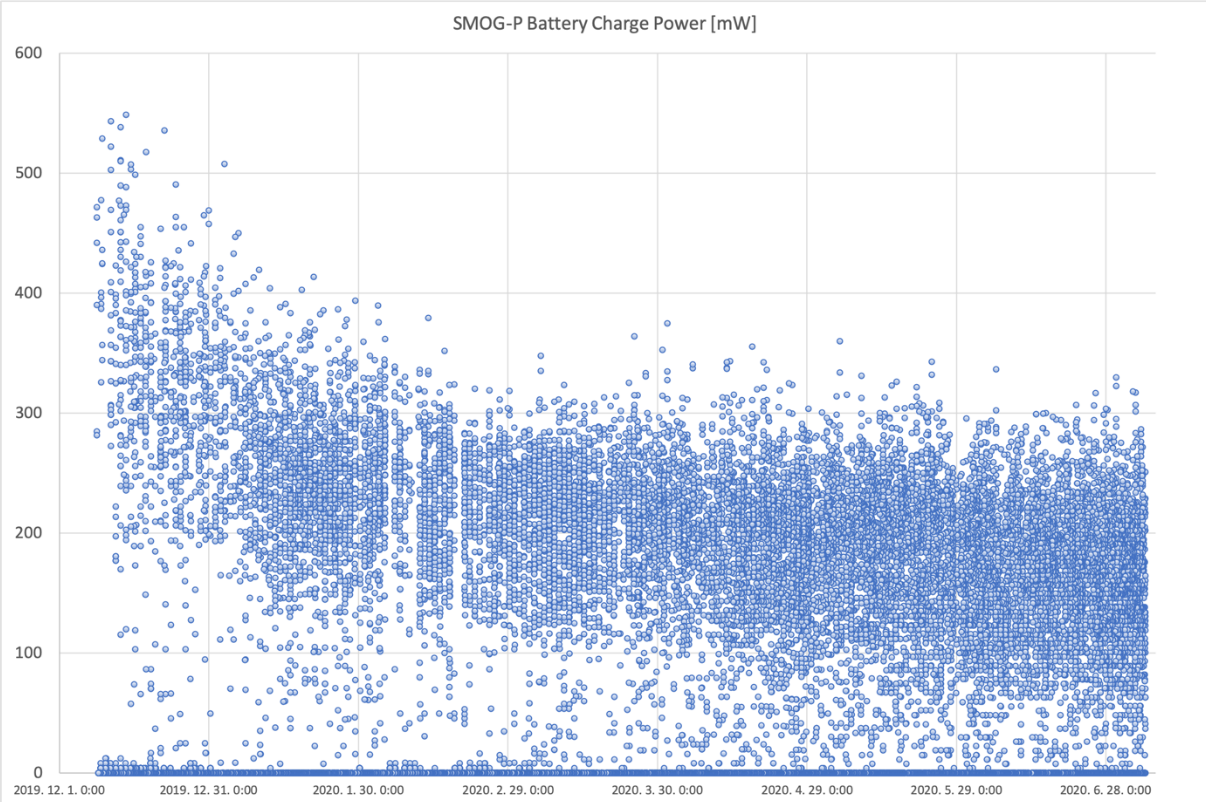
At the beginning of the mission everything worked as expected. After the launch the battery was nearly full, and only discharged to 85% during the dark periods. The solar power was enough to charge the battery back to 100% during the sunny parts of the orbit. Around 60% of SMOG-P's orbits are illuminated by the Sun while 40% of the path is shaded by Earth. The satellite makes a full orbit around Earth in every 91 minutes, the sunny and dark segments are repeating periodically.



7. Figure: Orbit simulation of SMOG-P around Earth

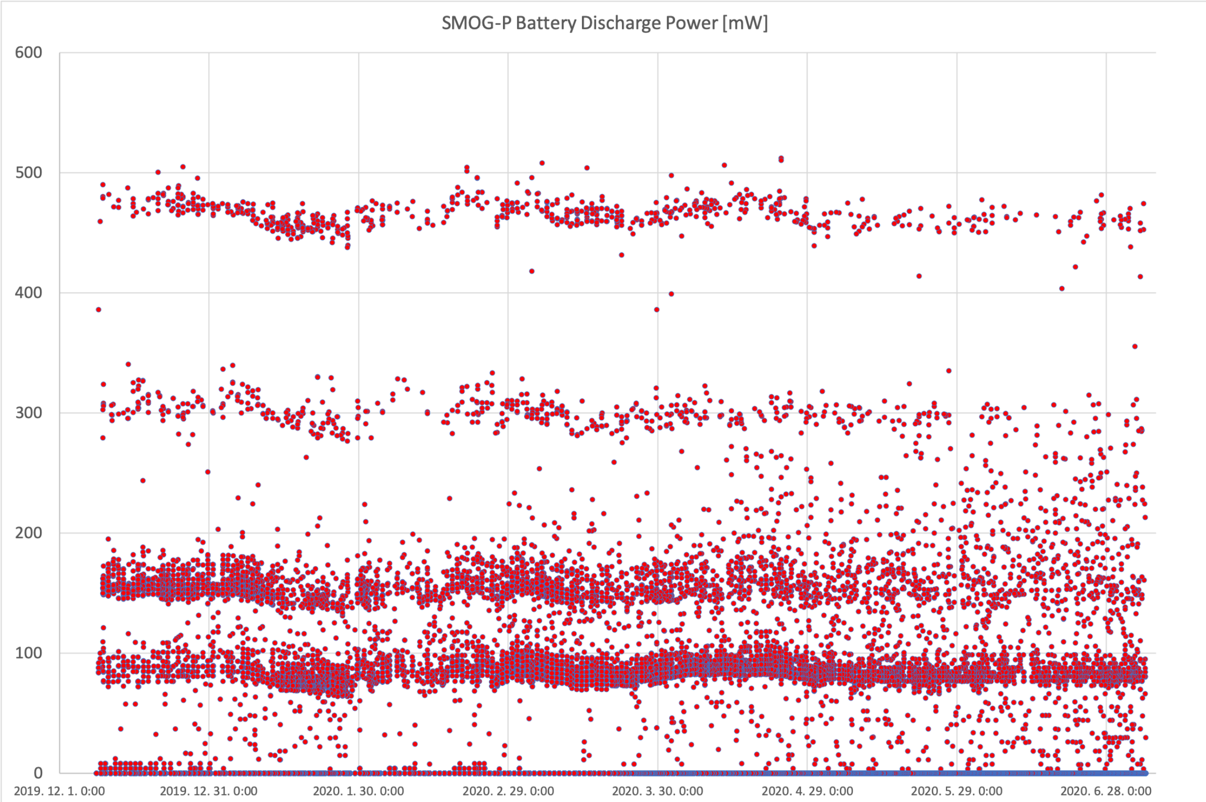
Unexpectedly the energy balance has changed during the mission. We noticed that the charge of the battery began to decrease, and after 10 days with slightly negative energy balance the satellite has reached a lower energy balance. SMOG is measuring the status of the battery continuously and in case of low battery charge it automatically tries to reduce the power consumption with the adjustment of the communication system which uses the most energy to establish reliable communication with the receiving ground stations that could be more than 2200 kilometers (1367 miles) away.

At the beginning of the anomaly we did not know what caused the drastic change in the energy balance. Thanks to the thousands of data packages, now we have a theory. The recorded data points of the battery charge power indicated that the incoming power from the solar cells has dropped dramatically compared to how it was at the beginning of the mission.



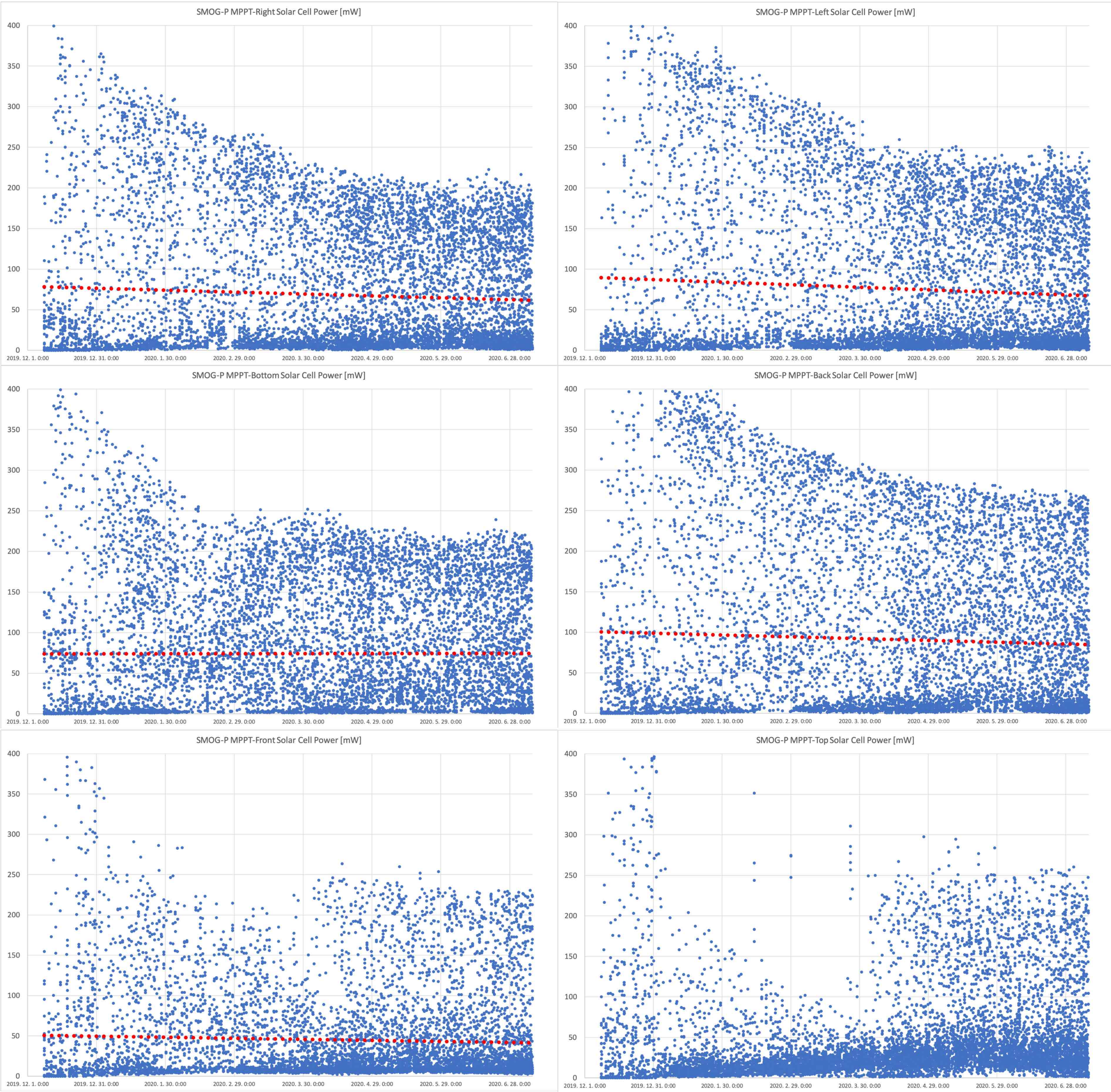
8. Figure: SMOG-P Recorded Battery Charge Power during the mission

The recorded charge power measurements of the battery are good indicators of the collected energy on one hand of the balance and the discharge power measurements are good indicators of the energy consumed by the satellite on the other hand. From the processed results it's clearly visible that the system tries to automatically compensate the missing incoming energy by spending more time in the low energy levels.



9. Figure: SMOG-P Recorded Battery Discharge Power during the mission

The satellite is measuring the voltages and currents of the solar cells, and this data made it possible to calculate the output power and the health conditions of the solar cells. These data gave us the information that all of the solar cells could only provide very reduced charge power levels.



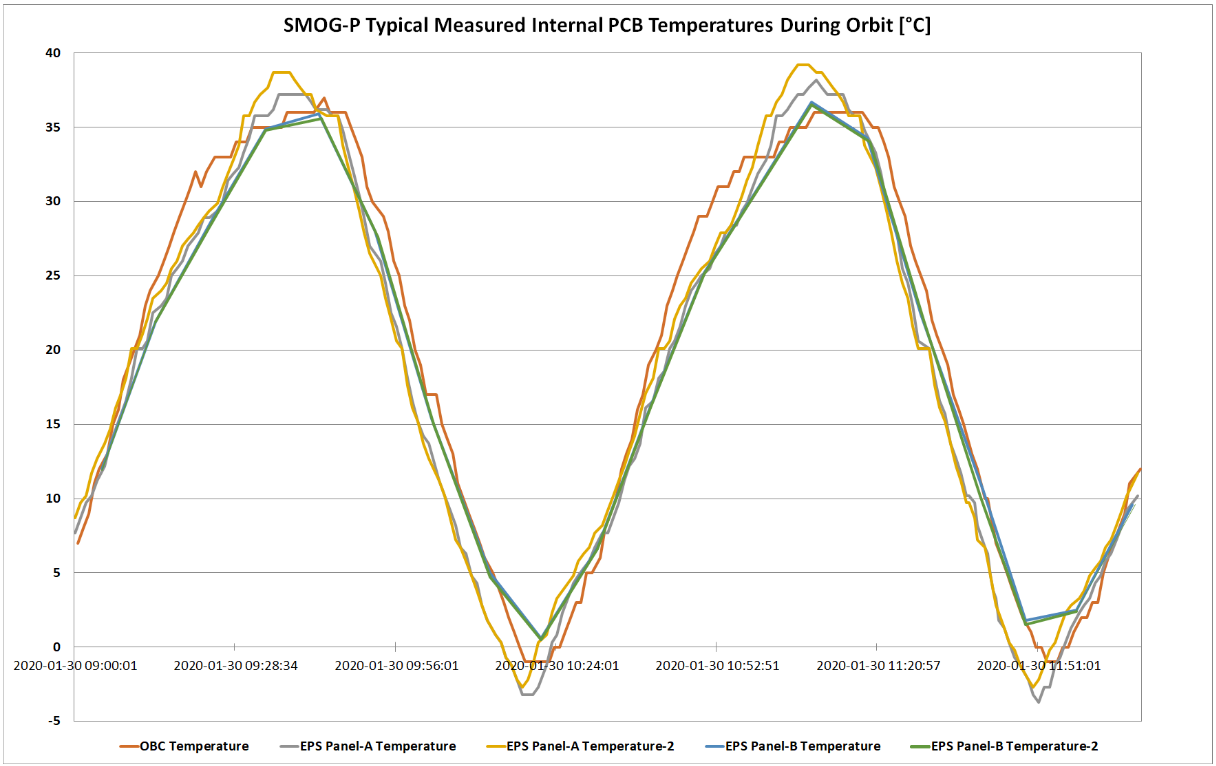
10. Figure: SMOG-P Recorded Solar Cell Power

The most likely reason is that unshielded space grade solar cells were used for the buildup. The protective layers are omitted from the cells, because we were only able to tailor and place them to the small sides of the satellite this way. This layer would be responsible to give some protection for the cells against radiation and Atomic Oxygen.

AO doesn't exist naturally for very long on the surface of Earth, as it is very reactive. But in space, where there is plenty of ultraviolet radiation, O_2 molecules are more easily broken apart to create atomic oxygen. The atmosphere in low Earth orbit is comprised of about 96% atomic oxygen. In the early days of NASA's space shuttle missions, the presence of AO caused problems. [1]

AO is nearly not present in the originally planned 600 km high altitude orbit, but have a much higher concentration in the lower 360 km altitude orbit on which SMOG-P started its mission. SMOG-P hits these particles with high relative speed (around 8 km/seconds), the most of

these particles hit by the solar cells since the biggest surface of the body is covered by the cells. The impacts could cause this kind of power degradation because the AO can corrode the silver that is used in the metallization of the cells.
There are a few other factors that could cause cell degradation, even though they are less likely. The temperature of SMOG-P is changing continuously, it's increasing in the sunny parts of the orbit and decreasing in the dark till the satellite reaches the sunlight again.



11. Figure: Measured temperatures and their fluctuation in the inner PCBs during orbit

Since SMOG has a small thermal capacity due to its small size and mass, this type of temperature variation is more extreme compared to other satellites with more thermal capacity. The results of the temperature sensors show that the inner sides of the outer PCBs changes between -20 and +70 °C (-4 and +158 °F) and the surface where the solar cells attached have probably bigger fluctuations that could cause mechanical stress and damage to the cells. The satellite already orbited the planet nearly 4000 times, which means the same number of thermal cycles. Space grade cells are designed to handle these conditions so the damages by this factor is less likely.
Radiation could also cause degradation of solar cells but according to our current knowledge and the results of the on-board dosimeter, Earth's magnetic field protects the low altitude orbit of SMOG-P well.

The satellite tries to continuously compensate the decreasing incoming solar power, thus the communication system's transmission timeframes are reduced, and the lack of the dissipated power cause a slow but detectable decrease of the average temperatures of the inner PCBs.

The satellite has been spinning since its launch. It was not feasible to build stabilization in this small volume. Because of the spin, the charging solar power is stochastic and it changes according to the number of the illuminated cells and their remaining performance. In some rare cases the battery was not charged enough during the sunny period and in these cases the protection circuit had to switch down the battery to protect it from overdischarge during the dark orbit segment. This caused the reboots of the satellite when it reached the sunlight again.

Despite the fact that the generated solar power is reduced to nearly the half of its initial value, SMOG-P was able to successfully finish the mission. The originally planned lifetime of SMOG was 3 months, and the satellite is still operational when these lines are written, about 8 months after its launch. The redundant systems are fully functional and we have not detected any circuit failures. The availability of the satellite is more than 99.98% regarding the short intervals when the battery was depleted during the end of some shaded orbit parts. Usually ground stations have less availability due to heavy storms and winds on the surface of Earth.

The degradation of the solar cells is also detectable in case of the ATL-1, which is a satellite built with the involvement of our team for a private company and launched together with SMOG-P. This satellite has two times the volume of SMOG-P, and due to its bigger surface covered by its solar cells, this satellite is not showing any anomalies yet except the previously mentioned single event latch-ups that is also happens often. The availability of ATL-1 is nearly 100%.

Our team have several possibilities to help SMOG-P with uplink commands if the solar power further decreases to a critical level. We can give an uplink command to the satellite to switch down the communication system when it is above the oceans, where there are no ground stations for reception and it’s not necessary to further measure the electromagnetic pollution. In this operation, the overall power usage of the satellite is only around 56 mW and any additional incoming power could be stored in the battery and can be used for communication above the control station. Due to its low altitude, the satellite will fall back in the atmosphere around October. The instruments will measure continuously until this happens if the incoming power will be sufficient for the operation, and hopefully we will have the possibility to examine the re-entry of such small satellite for the first time.

We prepared our next satellite SMOG-1 that is scheduled for launch in the end of 2020, and we reinforced the design based on the experiences collected during the mission of SMOG-P. SMOG-P proved that this construction is working well, and with the use of the current technology and knowledge, we are able to create such small and intelligent spacecrafts. SMOG-P will become a small shooting star in the atmosphere, it will not leave any space debris behind, only the useful scientific results and the countless experiences collected during the mission.

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06.08.2020 v1.2
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[1] https://www.nasa.gov/topics/technology/features/atomic_oxygen.html